

Sub-threshold production of $\Sigma(1385)$ baryons in Al+Al collisions at 1.9A GeV

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First measurement of sub-threshold $\Sigma(1385)$ production is presented. Experimental data are presented for Al+Al reactions at 1.9A GeV measured with the FOPI detector at SIS/GSI. The $\Sigma(1385)/\Lambda$ ratio is found to be in good agreement with the transport and statistical model predictions. The results allow for a better understanding of sub-threshold strangeness production and strangeness exchange reaction which is the dominant process for K^- production below and close-to threshold.

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Relativistic heavy ion collisions at SIS energies provide interesting opportunities for studying hot and dense nuclear matter. It allows to address fundamental aspects of nuclear physics such as the nuclear-matter equation-of-state [1, 2, 3, 4] and the question whether hadron properties undergo modifications in such an environment [5].

Indications for in-medium modifications of charged kaon production and propagation have been experimentally observed by the KaoS [6] and the FOPI [7, 8] collaborations at SIS energies. This beam energy range (1 - 2A GeV) is particularly well suited for studying in-medium properties of strange particles since, as they are produced below or close-to threshold, their production process is sensitive to nuclear in-medium effects. While sub-threshold K^+ are mostly produced via multi-step processes, transport models indicate that sub-threshold

K^- production results from strangeness exchange reactions $\pi + Y \leftrightarrow K^- + B$ whose rate is intimately linked to the hyperon ($Y = \Lambda, \Sigma$) yield [9, 10].

In addition, recent calculations based on the chiral theory predict an important coupling of the K^- to the medium via $\Sigma(1385)$, $\Lambda(1405)$ and $\Lambda(1520)$ resonances [11, 12, 13, 14] and reveal, in particular, the importance of the $\Sigma(1385)$ hyperon in sub-threshold K^- production [15]. Theoretical predictions on the in-medium cross-section of this strangeness exchange reaction differ widely [11, 12, 13, 14] and, on the other hand, experimental data on $\Sigma(1385)$ are scarce.

We report in this letter on the first measurement of charged $\Sigma(1385)$ (called Σ^* in the following) production in Al+Al collisions at a beam kinetic energy of 1.9A GeV. This measurement corresponds to sub-threshold produc-

tion since the threshold beam kinetic energy for Σ^* production in elementary reaction is $E_{\text{thr.}} = 2.33$ GeV. The measured yield is compared to the predictions of statistical and transport models. The only other available measurement of Σ^* production yield in heavy ion collisions has been reported recently by the STAR collaboration for the Au+Au system at the top RHIC energy ($\sqrt{s_{NN}} = 200$ GeV) [16, 17].

The experiment has been performed with the FOPI detector at the SIS Heavy-Ion Synchrotron of GSI-Darmstadt by using an Al beam of kinetic energy of 1.94 GeV on an Al target. The beam intensity was chosen to be $8 \cdot 10^5$ ions/s and the target thickness was 567 mg/cm^2 . The FOPI detector is an azimuthally symmetric apparatus made of several sub-detectors which provide charge and/or mass identification over nearly the full solid angle. The central part of the detector setup, placed in a super-conducting solenoid, consists of a Central Drift Chamber (CDC) surrounded by a barrel of plastic scintillators. The forward part is composed of two walls of plastic scintillators and a second drift chamber. For the present analysis, Λ and Σ^* were reconstructed from their decay products measured in the CDC ($23^\circ < \theta_{\text{lab}} < 114^\circ$). These are identified by their mass, which is determined from the correlation between magnetic rigidity and specific energy loss. More details about the configuration and performances of the different components of the FOPI apparatus can be found in [18, 19, 20]. The events were centrality selected by imposing conditions on the multiplicity of charged particles detected in the forward part of the detector. The results presented in the following correspond to the most central collisions ($\sigma_{\text{geo}} \leq 315$ mb) representing about 20% of the total geometrical cross section.

In order to assess the $P(\Sigma^{*-} + \Sigma^{*+})/P(\Lambda + \Sigma^0)$ ratio, yields of Σ^{*-} , Σ^{*+} as well as primary Λ have to be determined. Note that the reconstructed Λ yield includes decay Λ from Σ^0 which cannot be isolated with the FOPI detector because Σ^0 decays into a Λ and a photon. While primary Λ are reconstructed from the invariant mass of (p, π^-) pair candidates (see [21, 22] for more details about Λ reconstruction in FOPI), Σ^* are reconstructed from a topological analysis of their double two body decay:

$$\begin{aligned} \Sigma^{\pm} &\rightarrow \Lambda + \pi^{\pm} \quad (\text{BR} = 88\%, c\tau = 5 \text{ fm}) \\ &\hookrightarrow p + \pi^- \quad (\text{BR} = 64\%, c\tau = 7.89 \text{ cm}). \end{aligned}$$

Since the short life-time of the Σ^* does not allow to disentangle its decay vertex from the collision vertex, its reconstruction consists in correlating Λ with primary pions. Therefore, in order to minimize the combinatorial background in the (Λ, π^{\pm}) pair candidates, a high purity sample of Λ is extracted from the data. These Λ are reconstructed from identified pions and protons with the following conditions:

- i) a cut on momentum ($p_{\text{lab}} \geq 0.1$ GeV/c) is applied

in order to reject particles which are spiraling inside the CDC;

- ii) the distance of closest approach (DCA) between tracks and the primary vertex in the transverse plane ($\text{DCA}_p > 0.8$ cm, $\text{DCA}_{\pi^-} > 1.9$ cm) is used to enhance the fraction of protons and pions coming from a secondary vertex;

- iii) a cut on transverse flight distance ($d_t < 20$ cm) and on the pointing angle of the Λ ($\Delta\phi < 4^\circ$), the latter being the difference between the geometrical and kinematical azimuthal angles;

- iv) a cut on transverse momentum of the Λ in the laboratory ($p_t \geq 0.3$ GeV/c) is used to increase the purity of the signal.

The invariant mass of the particle pair is calculated from its four-momenta at the intersection point of the two tracks. The corresponding distribution is shown in the inset of Fig. 1. A total of about 10^5 Λ are reconstructed with a signal-to-background ratio close to 10 from the analysis of 290 million events. Σ^{\pm} are then reconstructed by calculating the invariant mass of these Λ with charged pions after applying a two-sigma mass selection cut around the Λ nominal mass (shown by the dashed lines in the inset of Fig. 1).

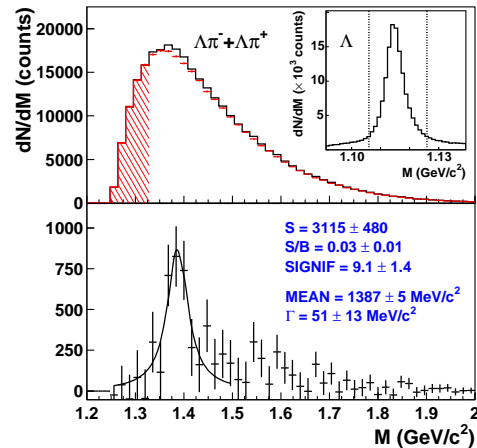


FIG. 1: Invariant mass spectra of $p\pi^-$ pairs (inset, upper panel) and $\Lambda\pi^\pm$ pairs. The solid histogram and crosses denote the data and the scaled mixed-event background, respectively (upper panel). The lower panel shows the signal after background subtraction. The following characteristics of the signal are shown: number of counts in the signal (S), signal-to-background ratio (S/B) and significance (SIGNIF). The parameters extracted from the fit to the data (mean mass value (MEAN) and the width (Γ)) are also reported.

The reconstructed Σ^{*-} and Σ^{*+} are shown in Fig. 1. The combinatorial background is obtained with the event-mixing method [23]. For that purpose, the two decay particles (Λ and π^\pm) are taken from two different events which present the same particle multiplicity in the CDC. In addition, the two events are aligned to the reaction plane in order to have the same reference

system for both particles. The reaction plane is estimated event by event utilizing the transverse momentum procedure detailed in [24]. In the invariant mass range 1.35 to 2 GeV/ c^2 , 16 excited states of Σ 's have already been observed [25]. Therefore, the normalization of the mixed background was done in the mass range 1.25 - 1.32 GeV/ c^2 (grey zone in the upper panel of Fig. 1) in order not to bias the reproduction of the combinatorial background. The shape of the resulting mixed-event background describes the combinatorial background and is indicated by crosses in Fig. 1 (upper panel). The vertical bars of the crosses correspond to the statistical errors. After background subtraction (Fig. 1, lower panel), the remaining peak in the mass spectrum is fitted with a Breit-Wigner function. Within the width interval (Γ), about 3100 $\Sigma^{*\pm}$ are found for the applied set of cuts in the analysis. The mean mass value and width extracted from the fit are in a good agreement, within statistical errors, with the values reported by the Particle Data Group [25]. The width of the Σ^* is expected to increase with baryonic density [26] but the accuracy of our measurement doesn't permit to draw any conclusion about a possible broadening. On the right side of the $\Sigma^{*\pm}$ signal, some excited states are visible as it has been observed in the invariant mass distribution presented by the STAR collaboration [16, 17].

The losses due to decay, acceptance and reconstruction efficiency have to be corrected in order to extract the particle yields. These corrections are determined by means of extensive GEANT simulations modeling the full detector response. The IQMD model [27] is used as generator for the underlying heavy-ion event. The $\Sigma^{*\pm}$ and Λ resonances are embedded in those events (one signal per event) and they are generated separately with a momentum distribution according to the Siemens-Rasmussen formula [28] which describes an expanding system with a temperature T and a radial expansion velocity β . The choice of the values of these parameters ($T = 90$ MeV, $\beta = 0$ and 0.3) is imposed by previous measurements [29, 30]. Afterwards, a full simulation of the detector, including resolutions in energy deposition and spatial position, Front-End-Electronics processing and tracking, is performed and the resulting output is subject to the same reconstruction procedure as for the experimental data. Simulated and experimental spectra of all relevant quantities were carefully compared. Since no significant differences were found, we conclude that the apparatus is properly described by the simulation [31, 32]. Finally, the reconstruction efficiency is determined by computing the ratio of reconstructed particles in the simulation to those initially embedded into the background events. The systematic error on the Λ and $\Sigma^{*\pm}$ yields was evaluated in two steps. First the reconstruction efficiency was estimated from simulated Λ and $\Sigma^{*\pm}$ with two values of the radial flow velocity ($\beta = 0$ and $\beta = 0.3$). Then the Λ and $\Sigma^{*\pm}$ signals were recon-

structed under different sets of conditions on the relevant quantities previously discussed (p_{lab} , DCA, d_t , $\Delta\phi$ and p_t). In order to minimize the statistical errors, the yields of Σ^{*+} and Σ^{*-} are summed and the following ratio can be extracted:

$$\frac{P(\Sigma^{*-} + \Sigma^{*+})}{P(\Lambda + \Sigma^0)} = 0.125 \pm 0.026(\text{stat.}) \pm 0.033(\text{syst.}).$$

Note that using such a ratio has the additional advantage that the influence of the chosen momentum distribution for the simulated signal is cancelled out to some extent. It is worth to point out that the measured ratio vary, within errors, by less than a factor two from SIS to RHIC despite the different processes involved in the Σ^* production [16, 17].

Our experimental ratio is compared to a statistical model predictions for Al+Al collisions [33]. The results are shown in Fig. 2 where other particle species such as proton, pion, Λ and K^0 are included.

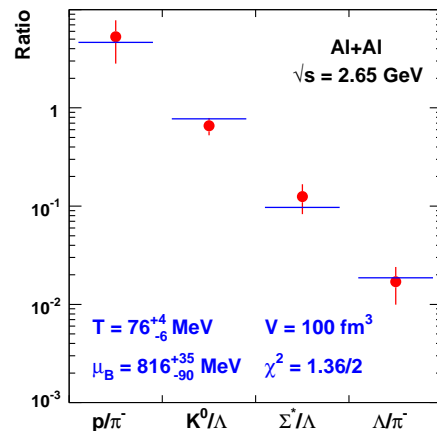


FIG. 2: Measured hadron yield ratios compared to the thermal model calculations for Al+Al collisions at 1.94 GeV. The symbols are data and the lines are the model calculations.

The statistical model, based on the canonical ensemble, reproduces the ratios with a temperature of 76 MeV and a baryonic chemical potential of $\mu_B = 816$ MeV. This chemical temperature is lower than the kinetical temperature of 95 ± 10 MeV derived from previous measurements [29, 30]. The same model, used to extract thermal parameters from Au+Au collisions at $\sqrt{s_{NN}} = 2.7$ GeV [33], reproduced particle ratios with $T = 64$ MeV and $\mu_B = 760$ MeV. It is surprising to notice that at the same energy, a lighter system (Al+Al) brings out higher temperature and baryonic chemical potential, while the volume represents 10% of the one of the Au+Au system. Finally, a higher temperature appears better suited to describe particle ratios when including a baryonic resonance and further studies on other strange particles including mesonic resonances as ϕ and $K(892)$ will be useful to constrain the temperature. As it has been reported in [34],

an additional parameter as γ_S which takes into account a non fully chemical equilibrium of strange particles could also be used to describe all the particle ratios.

The measurement is also compared to the prediction from the UrQMD transport model [35] for Al+Al collisions [36]. It is worth to point out that this model is the only transport code predicting Σ^* production at SIS energies. The results of comparisons with statistical and transport models are summarized in Tab. I.

| Yield ratio | Data | Therm. Model | UrQMD |
|--|-------------------|--------------|-------|
| $\frac{P(\Sigma^{*-} + \Sigma^{*+})}{P(\Lambda + \Sigma^0)}$ | 0.125 ± 0.042 | 0.097 | 0.177 |

TABLE I: Experimental yield ratio and predictions from statistical and transport models. The error of the experimental result corresponds to the quadratic sum of statistical and systematic errors.

The transport model prediction for Al+Al collisions is in relatively good agreement with the measurement when taking into account the upper limit of the error bars. The dominant process involved in the UrQMD model in order to produce Σ^* is the fusion of Λ and pions (76%) with an average cross section of about 37 mb [36]. The other processes used in the transport code to produce Σ^* are the interactions between Σ and pions (12%) and, N^* and Δ resonances with baryons (12%). The time dependence of these reactions exhibits a maximum around 8 fm/c which is in agreement with the predictions of the IQMD transport model [10] on the time production of strange particles such as kaons [37]. During the time span between the Σ^* production and the chemical freeze-out, about 8% of pions coming from the decay of the Σ^* are lost in inelastic interactions. This marginal loss could be attributed to the small size of the system created in Al+Al collisions.

In summary, we have presented new results about the $P(\Sigma^{*-} + \Sigma^{*+})/P(\Lambda + \Sigma^0)$ ratio in Al+Al collisions at 1.9A GeV. For the first time, the $\Sigma^{*\pm}$ resonances were measured 400 MeV below their production threshold. The experimental result was compared to the predictions of a statistical model and a transport model. The measurement is in good agreement with the transport model prediction where the dominant reaction to produce the Σ^* is the fusion of Λ and pions. On the other hand, the comparison with the thermal model suggests that a chemical freeze-out temperature of about 80 MeV is needed to describe the measured ratio.

The reported measurement should be used as an input for other transport codes for testing calculations on sub-threshold strangeness production. In addition, a measurement of the system size dependence of the Σ^* production, as well as other strange resonances, will give the opportunity to assess effects of a partial restoration of the chiral symmetry at high baryon density that can

be reached at SIS energies.

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